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UNIPOLAR DRIVE TOPOLOGY FOR PERMANENT MAGNET BRUSHLESS DC MOTORS AND SWITCHED RELUCTANCE MOTORS

RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. section 119(e) of the priority of U.S. Provisional Application No. 60/429,163, filed November 25, 2002,

5   entitled "Low-Cost Brushless DC Motor Drive with Improved Power Factor."

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field
10 of motor drives and, more particularly, to a unipolar drive topology for permanent magnet brushless DC motors and switched reluctance motors.

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BACKGROUND OF THE INVENTION

Cost minimization is important to the large volume manufacture and application of Brushless DC (BLDC) motors and Switched Reluctance Motors (SRMs) in variable speed drives. BLDC motors are conventionally excited with bipolar currents that require a six-switch inverter. The unipolar motor needs fewer electronic parts and uses a simpler circuit than the bipolar motor. For these reasons, unipolar-driven motors are widely used in low-cost instruments. The savings in converter cost opens up many applications for variable speed drives (VSD) such as HVAC, fans, pumps and appliances, which have been dominated by constant speed drives.

A simple unipolar drive includes a single switch in series with each winding and a Zener diode or dump resistor in the freewheeling path. This drive is inefficient because the stored energy in the phases is dissipated. Better performance may be obtained by using topologies that have previously been used for driving Switched Reluctance Motors (SRM). An example is the C-dump converter, which offers full regenerative control. However, it has the disadvantage of requiring a complicated control for the dump capacitor voltage, the failure of which could be catastrophic. A buck converter-based drive for the unipolar BLDC motor has also been proposed. Both these topologies require a higher voltage on the dump capacitors than what is applied to the motor phases during turn-on. While this is a requirement for the SRM motor in order to achieve a fast turn-off of the phase current to avoid negative torque spikes, it is not so for the BLDC motor. A three-

switch converter for the unipolar BLDC motor for ac supply operation was investigated, but it requires a modification in the machine windings and a split-capacitor voltage balancing control scheme.

5   For applications requiring operation from the utility supply, it is important to design the equipment to satisfy harmonics standards such as the IEC 1000-3-2, which limit the magnitude of current harmonics that can be injected into the utility. These standards are
10   typically not satisfied by the conventional method of AC/DC conversion using a bridge rectifier followed by a large DC bus capacitor. Passive Power Factor Correction (PFC) circuits based on the use of reactive elements are impractical in 50-60Hz single-phase lines because of
15   size, weight and cost. Active PFC methods are becoming increasingly popular because of the availability of low-cost switches. They include a DC-DC converter between the diode bridge and the bulk capacitor, which is controlled such that the input current is shaped to
20   follow the input voltage. The frequency spectrum of the input current would then consist of the fundamental plus easily filtered higher order harmonics. For low power levels, the extra cost and complexity of the additional PFC stage is not justified by the improvement in power
25   factor.

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SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, a unipolar drive includes a booster, an energy storage module, and a unipolar inverter. The booster
5   increase a voltage received from a power supply to produce an energy output. The energy storage module store at least some of the energy output by the booster. The unipolar inverter energizes windings of a motor using energy from the booster and returns energy from the
10   windings to the booster when the windings are not being energized.

In accordance with another embodiment of the present invention, a method for driving a motor includes receiving a voltage input from a power supply, boosting
15   the voltage received from the power supply, and energizing windings of the motor using the boosted voltage. The method further includes storing at least some of the energy not used by the windings to excite the motor and returning at least some of the energy stored in
20   the windings to the booster when the windings are not being energized.

Important technical advantages of certain embodiments of the present invention include low-cost unipolar inverters. Certain embodiments of the present
25   invention use a smaller number of switches than bipolar drives. This allows drives to be manufactured more cheaply, and provides advantages in situations where low-cost motors are advantageous, such as household appliances. In addition, differences in relative
30   capability and quality of performance between such low-

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cost drives and conventional drives is not significant for many applications using low-cost drives

Other important technical advantages of certain embodiments of the present invention include improved power factor over many conventional motors. Certain embodiments of the present invention store energy during the operation cycle of the motor and return energy that is frequently wasted in conventional unipolar drives, thus allowing a power factor near unity. This allows more efficient use of power, reducing the overall cost of operating the motor.

Still other technical advantages of the present invention include ground-referenced switches in the unipolar inverter. A motor drive according to one embodiment of the invention overcomes the disadvantage of using one or more high-side referenced switches in the converter topology. By using all ground-referenced switches, it simplifies the gate drive requirements and enables a low-cost and compact packaging.

Other technical advantages of the present invention will be readily apparent to one skilled in the art from the following figures, descriptions, and claims. Moreover, while specific advantages have been enumerated above, various embodiments may include all, some, or none of the enumerated advantages.

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BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and its advantages, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a schematic diagram of a particular embodiment of a unipolar drive topology for an electric motor;

FIGURE 2 shows a particular embodiment of a unipolar drive powered by a DC power supply; and

FIGURE 3 shows a particular embodiment of a unipolar drive powered by an AC power supply.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE
INVENTION

FIGURE 1 illustrates a unipolar drive 100 for an
electric motor 106. In the depicted embodiment, drive
5 100 includes a single-ended primary inductance converter
(SEPIC) front-end 102 coupled to a unipolar inverter 104.
Front-end 102 and unipolar inverter 104 in turn drive
motor 106, which is mechanically coupled to a load 112
driven by motor 106. In general, drive 100 uses power
10 received from a power supply 118 to drive motor 106 in a
consistent and controlled manner. Position sensors 114
provide information about the operation of motor 106,
thus allowing feedback to adjust the motor 106 in a
suitable manner to preserve smooth operation.

15   SEPIC front-end 102 is a circuit that maintains a
smooth flow of energy to drive motor 106. In the
depicted embodiment, front-end 102 includes a booster 108
and energy storage 110. Booster 108 increases voltage
received from power supply 118 through rectifier 116 to a
20 certain level. This level is determined by a reference
voltage (V_{ref}) that may be selected to be any suitable
level for insuring a consistent level of performance and
output from front-end 102. Booster 108 may also buck the
voltage to keep it below a certain level, which may be
25 useful when the windings of motor 106 are in certain
states of back-EMF. Energy storage 110 maintains energy
at times when it is not needed by unipolar inverter 104
to drive motor 106. Energy storage 110 provides energy
back to booster 108 in order to allow booster 108 to
30 maintain a consistent power level.

Unipolar inverter 104 includes switches coupled to windings (inductive components) of motor 106. When windings are energized, motor 106 is driven by unipolar inverter 104. Switches in unipolar inverter 104 control

5   the energy flow to windings, which in turn produce a back-EMF that removes energy from windings during the operation cycle. Unipolar converter 104 thus allows a motor 106 to be driven smoothly by incoming power from power supply 118.

10   Motor 106 may be any electric motor driven by unipolar inverter 104 to drive mechanical load 112, such as permanent magnet brushless DC motors (BLDCMs) or switched reluctance motors (SRMs). Motor 106 may include any of a variety of electric motors used in variable

15   speed applications. BLDCMs and SRMs are common in high volume air conditioning (HVAC), fans, pumps, and appliances. The control and drive topology for motor 106 is particularly useful because it allows variable speed BLDCMs to be used in areas which traditionally have been

20   dominated by constant speed drives.

Motor 106 is excited by unipolar excitation, a particular example of which may be described for the aforementioned surface-mount permanent magnet motor with concentrated stator windings. In such an embodiment of

25   motor 106, the induced back-EMFs with respect to rotor position are trapezoidal with a flat-top width that is as wide as possible. Smooth torque production requires forcing a constant current through each phase winding when its back-EMF is at its peak value and turning off

30   the current when the back-EMF is changing. This is accomplished in bipolar excitation by injecting positive

current when the back-EMF is positive, and negative
current when the back-EMF is negative, with each
conduction period lasting 120°. This results in two
phases conducting current and producing torque at any

5   instant of time. In contrast, unipolar current
conduction limits the phases to only one direction of
current. Constant torque production is still possible
because one phase is conducting current at any instant.
It is of course possible to have an overlap in the phase

10   conduction to have a smoother torque production.

Although unipolar excitation uses windings of motor
106 less efficiently, in that less output torque is
produced for the same peak currents, it has several
compensating advantages in terms of performance. First,

15   there is only one device in series with each phase,
minimizing conduction losses. Second, the risk of shoot-
through faults resulting from changing current directions
is eliminated. Third, switching of devices connected to
the supply rails, which generally requires some isolation

20   circuitry, can be avoided. In addition to these
performance advantages, there is significant potential
for reducing its cost. Typically, the inverter for a
motor costs more than the motor itself, so the relative
cost savings of reducing the number of components in the

25   inverter may be significant.

Position sensors 114 monitor the location of rotor
106. The position information maintained by position
sensors 114 may in turn be used to determine the speed of
motor 106. This allows adjustment of the speed as

30   necessary. In a particular embodiment, position sensors
114 are coupled to unipolar inverter 104 and a speed

estimator 128. Speed estimator 128 calculates the speed of the motor 106 based on position measurements, allowing proper feedback to be determined for unipolar inverter 104 controlling motor 106.

5   Rectifier 116 and power supply 118 provide power to front-end 102 that is used to drive motor 106. In the depicted embodiment, power supply 118 represents any suitable source of alternating current power. Rectifier 116 converts AC power from power supply 118 to DC power,

10   which is then used by front-end 102 to drive motor 106.

Feedback during the operation of motor 106 is provided by a variety of components. Front-end 102 is controlled based on a comparison of a voltage into inverter 104 performed by comparator 120. An

15   intermediate capacitor 134 between front-end 102 and unipolar inverter 104 follows the input voltage from front-end 102. This input voltage is measured across resistors 136. The input voltage (V_i) is measured against V_{ref} by comparator 120. Based on that comparison, a

20   signal is provided to proportional controller and limiter, shown by box 122. This sets the level of output signal from comparator 120 to an appropriate value. The signal is then provided to pulse width modulation comparator 124, which in turn provides feedback to front-

25   end 102 for adjustment of boosting level of booster 108.

Feedback on the speed of motor 106 is provided to inverter 104 to allow adjustment of drive 100. Position sensors 114 provide position information to speed estimator 128 which determines a frequency (ω) for motor

30   109. Frequency ω is compared to a reference frequency (ω_{ref}) by comparator 126. The results of this comparison

are provided to proportional and integral controller and limiter, shown by box 130. This sets the output level of comparator 126 accordingly. The resulting signal is provided to hysteresis comparator 132. Hysteresis
5   comparator 132 receives information about the drive signals provided to motor 106, and information about the frequency of the motion of motor 106 from box 130. Using this information, hysteresis comparator 132 controls gates of switches in unipolar inverter 104 to make
10 suitable adjustments to the control of windings provided by unipolar inverter 104.

In operation, front-end 102 receives power signals from power supply 118 that have been rectified by rectifier 116. Front-end 102 appropriately boosts the
15 power of these input signals using energy stored in energy storage 110. Front-end 102 provides a boosted output to intermediate capacitor 134 which in turn follows the input and provides it to unipolar inverter 104. Unipolar inverter 104 energizes windings of motor
20 106 to produce motion in load 112.

During operation, front-end is controlled by feedback from comparator 120. Thus, as the input voltage measured over intermediate capacitor 134 moves above or below a certain threshold, comparator 120 adjusts a
25 switch in booster 108 to adjust level of boost provided by front-end 102. Similarly, using position information from position sensors 104, comparator 126 provides feedback to unipolar inverter 104 to obtain the correct frequency of motion in motor 106 by controlling the
30 windings of motor 106.

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FIGURE 2 shows a particular embodiment of unipolar drive 100. Drive 100 includes unipolar inverter 104, booster 108, and energy storage 110. Booster 108 and energy storage 110 collectively form front-end 102. The

5   particular arrangement of components shown is only one example of a circuit that can perform as unipolar drive 100, and other configurations that perform equivalent functions should be understood to be included in the associated description.

10   Unipolar inverter includes switches 202A, 202B, and 202C (collective referred to as "switches 202"), which control the energizing of windings 204A, 204B, and 204C (collectively referred to as "windings 204"), also known as "phases." Inverter 104 also includes diodes 206A,

15   206B, and 206C (collectively referred to as "diodes 206"), which provide energy back to booster 108 when windings 204 are discharged. This allows energy that might be lost in operation of motor 106 to be conserved for later use by drive 100. Switches 202 are shown as

20   transistors which are switched on and off based on signals provided to their respective gates by hysteresis comparator 132. Thus, hysteresis comparator 132 controls operation of switches 202. When switches 202 are allow current to flow, energy flows through windings 204, thus

25   energizing them. When switches 202 interrupt current flow, energy stored in windings 204 passes through diodes 206 back to booster 108.

In the depicted embodiment, booster 108 includes switch 208, inductor L_1 210, and capacitor C_1 212.

30   Booster 108 is coupled to energy storage 110. Energy storage 110 is an LC tank that includes inductor L_2 214,

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capacitor C_2 216, and diode D_1 218, which allows energy to flow from energy storage 110 back to booster 108. Drive 100 is powered by a DC power supply 220. Thus, rectifier 116 is not used in the depicted embodiment.

5   In operation, each phase is energized by turning on the corresponding switch in series with it. To regulate the current, switch 202A is turned off, which forces the turn-on of diode 206A, and the flow of current through C_1 212. This applies a voltage of $-V_{C1}$ across the machine

10   winding 204A, enabling a fast decay of the phase current. For proper demagnetization of phase 204A after each conduction interval and to prevent conduction during periods of negative back-EMF, the instantaneous value of V_{c1} should be greater than the peak value of the back-EMF

15   E, or

$V_{C1} > E$ (1)

By applying Kirchoff's voltage law to front-end 102, the following equation is obtained:

$$V_{in} = V_{L1} + V_{C1} + V_{L2}$$

20   Since the average voltages in the two inductors 210 and 214 are zero, it follows that

$$V_{in} = V_{C1}$$ (2)

From (1) and (2), the peak back-EMF is obtained at the maximum speed of motor 106, which is given by $E_{max} =$

25   V_{in}, assuming that the ripple in the intermediate capacitor voltage is negligible. The maximum operating speed is then given by

$$\omega_{max} = \frac{V_{in}}{K_e}$$ where K_e is the phase back-EMF constant of the motor.

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If motor 106 is operated beyond this speed, it would result in negative torque spikes because of conduction during periods of negative back-EMF.

The minimum voltage V_{dc} required under these conditions in this embodiment is

$$V_{dc} = E + IR_s + L_s \frac{dI}{dt},$$

where R_s and L_s are the phase resistance and inductance, and I is the phase current. At low speeds, when the back-EMF is low, the switching frequency of the phase switches increases in order to regulate the phase current. The switching frequency and hence the losses at low speeds can be minimized by bucking the input voltage to lower levels at the output V_{dc}. At higher speeds, the current regulator loses its ability to force current into the phases especially during turn-on because of the high back-EMF voltage. The ability of front-end 102 to boost the available input voltage makes it possible to maintain current-regulated operation of the drive at higher speeds. This feature makes the proposed topology particularly suitable for low voltage DC applications such as automotive circuits.

Front-end 102 can be designed for operation either in the Continuous Conduction Mode (CCM) or in the Discontinuous Conduction Mode (DCM). In CCM, its voltage conversion ratio is given by

$$m = \frac{V_{dc}}{V_{in}} = \frac{D}{1-D},$$ where D is the duty cycle of the switch

S_1.

In DCM, its voltage conversion ratio is given by

$$m_d = \frac{V_{dc}}{V_{in}} = \frac{D}{\sqrt{K}}, \quad \text{where} \quad K = \frac{2L_1 L_2}{RT(L_1 + L_2)}, \quad \text{R being the}$$

equivalent load resistance and T the time period of switch S_1.

The boundary value of K between continuous and discontinuous conduction modes, K_{crit} can be calculated ($m = m_d$) as:

$$K_{crit} = (1 - D)^2$$

The converter operates in CCM when K > K_{crit} and in DCM when K < K_{crit}. In both modes of operation, V_{dc} can be regulated at a value higher (Boost operation) or lower (Buck operation) than the input voltage V_{in}. From the controls viewpoint, it is advantageous to have the converter operating in the same mode under all load conditions. In addition, the size of the inductors and hence the overall converter can be reduced if it is operated in DCM. Hence, it is proposed in one embodiment that the converter be designed for operation in the critical conduction mode at maximum load, so that it operates in DCM at rated load and all values less than rated load, but it should be understood that alternative embodiments in CCM or a combination of both modes are also possible.

Sample calculations for component values of the described DCM embodiment may be performed as well. In one example, a DCM embodiment of drive 100 is used to drive a commercially available fractional horsepower BLDC motor with a phase back-EMF constant of 12V/Krpm. Because of the low back-EMF constant, the input voltage is chosen to be 50V peak. A drive with a power rating of

100W is designed.   The following equations are used to design the component values [9]:

Input voltage v_{ac} = 50 sin($2\pi60t$) V

DC bus voltage v_{dc} = 24 V

5   Switching frequency of S_1, f_s = 25KHz

Voltage conversion ratio M = 24/50 = 0.48

Critical conduction parameter $K_{a,crit}$ = $0.5/(M+1)^2$ = 0.228

K_a = 0.16 is chosen to ensure DCM operation

10   Duty cycle of S_1, d = $\sqrt{2}M\sqrt{Ka}$ = 0.271

Equivalent inductance L_{eq} = $RT_sK_a/2$ = 28.8μH

Input current ripple I_{rip} = $20\%I_1$ = 0.8A

L_1 = V_1dT_s/I_{rip} = 677μH

L_2 = $L_1L_{eq}/(L_1-L_{eq})$ = 30μH

15   C_1 = $1/(\omega^2(L_1+L_2))$ = 5.8μF.   Actual values of C_1 selected will be higher than the calculated value in order to reduce the voltage ripple caused by the freewheeling phase currents.   A value around 10μF would allow sufficient voltage stability for most applications.

20   In operation, booster 108 imparts a boost to the input power signal from power supply 220 according to the control provided by comparator 120 coupled to gate of switch 208.   The amount of boost is controlled by opening and closing switch 208.   This is also influenced by a

25   freewheeling current (i_{fw}) returned from unipolar inverter 104 by diodes 206.   Excess energy is stored in inductor L_2 214 and capacitor C_2 216.   Energy from energy storage 110 may be provided to booster 108 through diode D_1 218.

The energy provided from front-end 102 in turn

30   energizes motor 106.   The manner in which windings 204 are energized is controlled by switches 202.   Switches

202 are in turn controlled by hysteresis comparator 132 which provides voltages to the gates of switches 202. As a result, motor 106 may be smoothly and efficiently driven by drive 100.

5   FIGURE 3 is an alternative embodiment of drive 100 driven by an AC power supply 320. In this case, rectifier 116 is used to convert AC power from AC power supply 320 to DC power. In the depicted embodiment, rectifier 116 includes four diodes 322 in the arrangement

10   of a diode bridge. All other components of drive 100 are analogous to those described in FIGURE 2. For example, switches 302 correspond to switches 202, windings 304 correspond to windings 204, and diodes 306 correspond to diodes 206. The operation of the depicted circuit is

15   substantially the same apart from the fact that the DC voltage provided is rectified from AC power supply 320. It is notable, however, that the voltage is able to substantially follow the input voltage from AC power supply 320.

20   FIGURE 4 shows an example method of operation for drive 100 powered by AC power supply 320. Drive 100 receives voltage from power supply 320 at step 402. Rectifier 116 rectifies the voltage signal from power supply 320 at step 404. Booster 108 boosts the voltage

25   provided by power supply 320 at step 406. The resulting energy is used to power windings 304 at step 408. Energy not used by windings is stored by energy storage module at step 410. When windings are not being energized, energy from windings is returned to booster 108 using

30   diodes 306 at step 412. These steps may be repeated as long as motor 106 is in operation, as shown by decision

step 414. The particular method of operation described here is only one particular example, and any other method consistent with the description of drive 100 provided above may also be used.

5   Although the present invention has been described with several embodiments, a myriad of changes, variations, alterations, transformations, and modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass

10   such changes, variations, alterations, transformations, and modifications as fall within the scope of the appended claims.